2.1 Momentum

Figure B2.1: There are hockey players in most commercial leagues who can shoot a puck at velocities over 130 km/h.

The image of the hockey puck streaking toward the goalie's mask is certainly frightening, but what properties of the motion of a puck are cause for concern? Analyzing the motion of a puck and using the results from the "Characteristics of an Object in Motion" activity should enable you to initially identify two basic properties of moving objects: mass and velocity. But how are mass and velocity really causes for concern?

The mass of an object is a property that has several definitions, such as "the quantity of matter" or "the amount of inertia" (measured in kilograms) of an object at rest. Although mass is a property that is difficult to define, you likely have a fairly good idea of the effects of mass. For example, a vehicle with a larger mass is more difficult to stop than a vehicle with a smaller mass.

Figure B2.2: A penalty kick in soccer is one of the most difficult shots to defend.

A puck and a soccer ball have different masses. In comparison, the mass of the hockey puck is 0.170 kg, whereas the mass of a soccer ball is 0.425 kg (about three times that of a puck). This means that the soccer ball has three times the quantity of matter (or three times the inertia) of the puck; yet, a goalkeeper in soccer does not wear the same protective gear as a goaltender in hockey.

In Chapter 1 you studied the property of velocity and used it to describe the motion of an object. Again, in comparison, a puck can reach velocities of over 160 km/h, while a tennis ball can reach velocities of over 200 km/h. Why is it that tennis players do not wear protective gear?

Is the mass of an object by itself a property that is cause for concern? What about velocity by itself? Why is it necessary for hockey players to wear protective gear but not soccer or tennis players?

Using his first law of motion, Isaac Newton reasoned that since an object with a large mass at rest has more of a tendency to stay at rest, perhaps an object with a larger mass moving with a greater velocity must have more of a tendency to remain in motion. Newton referred to the product of an object's mass and its velocity as its "quantity of motion." The modern term for this is **momentum**. The equation for momentum summarizes these ideas.

momentum: the product of an object's mass and its velocity

Figure B2.3: A powerful forehand shot in tennis can leave the defender with little time to react.

$$\vec{p} = m\vec{v}$$

momentum (kg·m/s) | mass (kg) | velocity (m/s)

Note that since velocity is a vector, the product of mass (a scalar) and velocity must also be a vector. In the example problems that follow, you will see how the direction of the momentum vector is automatically the same as the direction of the velocity vector, and vice versa.

Example Problem 2.1

Determine the momentum of a vehicle with a mass of 2100 kg moving at a velocity of 22 m/s[E].

Solution

Let east be the positive direction.

$m = 2100 \text{ kg}$

$\vec{v} = 22 \text{ m/s[E]}$

$= +22 \text{ m/s}$

$\vec{p} = ?$

$\vec{p} = m\vec{v}$

$= (2100 \text{ kg})(+22 \text{ m/s})$

$= +4.6 \times 10^4 \text{ kg·m/s}$

The momentum of the vehicle is 4.6×10^4 kg·m/s[E].

Example Problem 2.2

The total momentum of a motorcycle and rider is 7.20×10^3 kg·m/s[S]. If the combined mass is 250 kg, determine the velocity of the motorcycle and the rider.

Solution

Let south be the negative direction.

$\vec{p} = 7.20 \times 10^3 \text{ kg·m/s[S]}$

$= -7.20 \times 10^3 \text{ kg·m/s}$

$m = 250 \text{ kg}$

$\vec{v} = ?$

$\vec{p} = m\vec{v}$

$\vec{v} = \dfrac{\vec{p}}{m}$

$= \dfrac{-7.20 \times 10^3 \text{ kg·m/s}}{250 \text{ kg}}$

$= -28.8 \text{ m/s}$

The velocity of the motorcycle and rider is 28.8 m/s[S].

Example Problem 2.3

An airplane has a momentum of 8.3×10^7 kg·m/s[N]. If the airplane is flying at a velocity of 990 km/h[N], determine its mass.

Solution

Let north be the positive direction. This solution involves dividing momentum by velocity. Recall that multiplying or dividing one vector by another is beyond the scope of this course. Therefore, the vector notation is dropped.

$$p = 8.3 \times 10^7 \text{ kg·m/s[N]}$$
$$= +8.3 \times 10^7 \text{ kg·m/s}$$

$$v = 990 \text{ km/h[N]}$$
$$= +990 \frac{\text{km}}{\text{h}} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ h}}{3600 \text{ s}}$$
$$= +275 \text{ m/s}$$

$$m = ?$$

$$p = mv$$
$$m = \frac{p}{v}$$
$$= \frac{+8.3 \times 10^7 \text{ kg·m/s}}{+275 \text{ m/s}}$$
$$= 3.0 \times 10^5 \text{ kg}$$

The mass of the airplane is 3.0×10^5 kg.

Practice

1. While stepping off a skateboard, the rider propels the skateboard with a velocity of 2.50 m/s[N]. If the mass of the skateboard is 2.2 kg, calculate the momentum of the skateboard.
2. A 900-kg car has a momentum of 1.35×10^4 kg·m/s[E]. Calculate the velocity of the vehicle.
3. A ball thrown with a velocity of 32.0 m/s[W] has a momentum of 4.5 kg·m/s[W]. What is the mass of the ball?

Momentum and Protective Equipment in Sports

Momentum plays an important role in explaining the necessity of protective equipment in sports. For example, the combination of the mass and the velocity of a hockey puck gives it more momentum than the momentum of the tennis ball. But this is not the whole story. Although soccer balls generally travel at lower velocities than hockey pucks, their larger mass means that they can have the same momentum as a puck. What makes being hit with a puck so much more dangerous than being hit with a soccer ball?

Figure B2.4: A soccer ball, hockey puck, and tennis ball can possess the same momentum.

Another important characteristic of moving objects is their ability to be compressed upon impact. Even though hockey pucks are made from rubber, they are frozen hard before games to make them even more rigid. This reduces the puck's tendency to bounce. Soccer balls, on the other hand, must be able to bounce; they have to have an elastic surface that can momentarily change shape. As you'll see later in this chapter, the ability of an object to be compressed upon impact relates to the concept of change in momentum. This will become important as you further explore the designs of protective sports equipment and automotive safety systems.

2.1 Summary

The combination of the properties of mass and velocity yield a new property for all objects, which was originally called the "quantity of motion." The product of an object's mass and its velocity is now known as the object's momentum. The momentum of an object is quantified using $\vec{p} = m\vec{v}$. It is important to remember that momentum is a vector quantity; therefore, magnitude and direction must be stated. A moving object has a large momentum if it has a large mass, a large velocity, or both.

2.1 Questions

Knowledge

1. State another term for "quantity of motion."

2. Identify the two factors used to determine the momentum of an object.

Applying Concepts

3. Calculate the momentum of a 40.0-kg wagon moving 1.90 m/s[N].

4. A 0.170-kg hockey puck slides across the ice with a momentum of 1.60 kg·m/s[E]. Determine the velocity of the hockey puck.

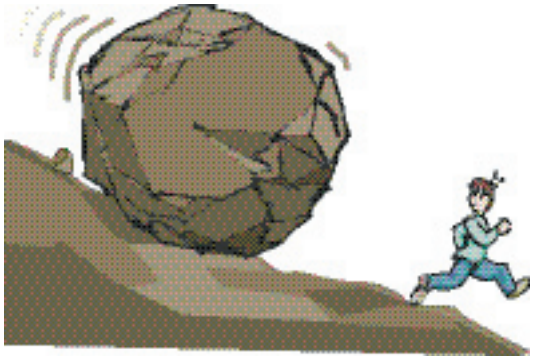
5. Calculate the mass of a billiard ball given that it has a momentum of 0.320 kg·m/s[N] and a velocity of 2.0 m/s[N].

6. A vehicle with a mass of 40 000 kg is travelling 80.0 km/h[S]. Calculate the momentum of this vehicle in kg·m/s.

7. Use your analysis from the "Characteristics of an Object in Motion" activity (on page 241) and your understanding of the concept of momentum to answer questions 7.a. and 7.b.

a. Explain how the ability of the marbles to move the cup cannot be explained using only
- **i.** the marble's mass
- **ii.** the marble's velocity

b. Describe how the marbles demonstrate
- **i.** inertia
- **ii.** momentum

c. Apply your understanding of momentum to explain the behaviour of the marbles in the activity.

8. If the rock and the person in the cartoon on the right both have the same momentum, will the rock hit the person? Justify your answer.